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PRELIMINARY INVESTIGATION AND DESIGN OF AN AIR-HEATED WING FOR LOCKHEED 12A AIRPLANE

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INTRODUCTION

Information obtained by the National Advisory Committee for Aeronautics in ice-prevention tests indicates that the most effective method of preventing the formation of ice is that of heating the surfaces to be protected. The use of waste heat in the exhaust gases as a source of heat energy and the dynamic head in flight as a pump to circulate heated air has been proven practical in a series of test flights. In recent flight tests (reference 1) the exhaust gases were passed through the leading edge of the wings and ejected at the wing tips. Circulated air was passed over the exhaust tube inside each leading edge, then into the after part of the wing, and out to the atmosphere through louvers which were located near the aileron and flap hinges. Effective ice protection in all kinds of icing weather was obtained. Objections have been raised to the use of an exhaust gas tube in the wing leading edge, particularly by the military services.

Further study of de-icing methods indicates that effective ice prevention can be obtained by the passage of heated air through the interior of the part or surface to be protected. The source of the heated air may be an independent unit heater which burns gasoline or other substance, or an exhaust-air heat exchanger. The latter is thought to have considerable merit and is being employed by the NACA in current ice-prevention investigations. The pressure required for circulation of the heated air through the heater and the heated surfaces is produced by the dynamic pressure of the air stream.

In this report there are presented a study of the design of an air-heated wing and the results of tests performed on a model air-heated leading edge, which were made to determine the validity of the proposed wing design.

PRELIMINARY DESIGN PROCEDURE

A study of the possible ways by which heated air could be applied to the airplane wing or other lifting surface resulted in the selection of a design, the leading edge of which is shown in figure 1. Referring to figure 1, air is passed spanwise along an unobstructed duct, region 1, from which it flows chordwise into a gap between the double-skin leading edge, region 2. After leaving region 2, the air flows through passages permitted by the normal voids and lightening holes in the conventional metal airplane wing, and is discharged to the atmosphere through suitable ducts or louvers near the aileron and flap hinges. In this design the following factors are important:

1. The mass flow of the air through the gap
2. The size of the gap
3. The temperature of the air in the duct
4. The pressure required to pass the heated air through the gap

NOMENCLATURE

Q_{1-5} heat taken from air as a result of passing through the gap, Btu/hr

Q_{2-3} heat transferred from air to wing leading-edge skin, Btu/hr

Q_{3-4} heat lost by skin, Btu/hr

h_{2-3} heat transfer coefficient from air in gap to outer skin, Btu/hr, sq ft, $^{\circ}F$

h_{3-4} heat transfer coefficient from leading edge to ambient air, Btu/hr, sq ft, $^{\circ}F$

A area of heated outer skin, sq ft

W mass flow through gap, lb/hr

c_p	specific heat of air in the gap, Btu/lb, °F
t_1	temperature of air in duct, °F
t_2	mean temperature of air in gap, °F, $\left(\frac{t_1 + t_5}{2}\right)$
t_3	temperature of outer skin, °F
t_4	temperature of ambient air, °F
t_5	temperature of air out of gap, °F
μ	absolute viscosity of air in gap, lb/hr ft
k	thermal conductivity of air in gap, Btu/hr, sq ft, °F/ft
d	gap thickness, ft
G	mass flow per unit sectional area of gap, lb/hr ft^2
p_1-p_5	pressure drop through gap, lb/sq ft
v_5-v_1	change in specific volume, ft^3/lb
f_{av}	friction coefficient at average air temperature
N	length of gap, ft
v_{av}	average specific volume, ft^3/lb
m	hydraulic radius of gap, ft
g	acceleration of gravity, ft/hr^2
Re	Reynolds number, $\frac{dG}{\mu}$
Nu	Nusselt number, $\frac{hd}{k}$
σ	Prandtl number, $\frac{c_p\mu}{k}$

It is assumed that the fundamental relations for the flow of air through circular pipes remain true for the flow through the gap of region 2, figure 1, basing the gap Reynolds number upon the gap thickness. The principal relations used in these calculations are as follows:

$$Q_{3-4} = h_{3-4}A(t_3-t_4) \tag{1}$$

$$Q_{2-3} = h_{2-3}A(t_2-t_3) \tag{2}$$

$$Q_{1-5} = Wc_p(t_1-t_5) \tag{3}$$

$$Q = Q_{1-5} = Q_{2-3} = Q_{3-4} \tag{4}$$

$$\frac{h_{2-3}d}{k} = 0.0225\left(\frac{dG}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)^{0.4} \tag{5}$$

$$p_1-p_5 = \frac{G^2(v_5-v_1)}{g} + \frac{f_{av}NG^2v_{av}}{2\ gm} \tag{6}$$

The symbols and equation forms are the same as those employed in reference 2.

For a solution of the problem of heat transfer from the air in region 2 to the airfoil skin, region 3, consider 1 foot of span and one passage, that is, either along the upper or lower surface. A simplification of equation (5), which admits the use of air as the gas involved and the characteristics of air over the temperature and pressure ranges in the problem at hand, gives

$$Nu = \frac{h_{2-3}d}{k} = 0.02\ \left(\frac{dG}{\mu}\right)^{0.8}$$

When the 1-foot span is considered $G = \frac{W}{d}$ and therefore

$$\frac{hd}{k} = 0.02\left(\frac{W}{\mu}\right)^{0.8} \tag{7}$$

in which W is the weight of air passing through the 1 foot of gap. Equation (7) may also be written as

$$h = \frac{0.02k}{\mu^{0.8}} \times \frac{W^{0.8}}{d} \tag{7a}$$

The values for k and μ which apply with satisfactory accuracy over the range of the present problem are

$$k = 0.017 \text{ Btu/hr, } {}^{\circ}\text{F, ft}^2\text{/ft}$$

and

$$\mu = 5.62 \times 10^{-2} \text{ lb/hr, ft}$$

These values substituted into equation (7a) give

$$h = 0.0034 \frac{W^{0.8}}{d} \tag{7b}$$

From reference 3 the heat transfer from the leading-edge surface of an airfoil is given by the equation

$$h_{3-4} = h'' \frac{C''}{C'} \left(\frac{V'C'}{V''C''}\right)^n \tag{8}$$

In the present problem $C' = 93.4$ inches, $V' = 135$ mph; from reference 3, $h'' = 28$ Btu/sq ft, °F, hr, $C'' = 10$ inches, $V'' = 80$ mph, and $n = 0.52$ at the estimated angle of attack for cruising speed; and from equation (8), by calculation, $h_{3-4} = 12.6$ Btu/ft², °F, hr.

Previous flight tests have indicated that effective icing protection was obtained when the forward 12 to 15 percent of the wing leading-edge skin was maintained at an average temperature of about 75° F above that of dry ambient air. The temperature rise of the afterbody decreased from about 75° F at the 12-percent-chord point to 10° F at the 75-percent-chord point.

The amount of heat required to raise the leading-edge skin temperature 75° F above ambient air temperature is found from the relation:

$$Q_{3-4} = h_{3-4}A(t_3-t_4)$$

Let it be assumed that the ambient air temperature t_4 is equal to 0° F and that the skin temperature over the leading-edge region t_3 is equal to 75° F, as suggested above. Considering 1 square foot of area for which h_{3-4} is equal to 12.6 Btu/hr, °F, then

$$Q_{3-4} = 12.6 \times 1 \times (75-0) = 945 \text{ Btu/hr}$$

which is the quantity of heat transmitted from the leading-edge skin to the ambient air stream over 1 square foot.

From equations (3) and (4)

$$Wc_p(t_1-t_5) = 2\ Wc_p(t_1-t_2) = 945$$

and therefore

$$t_2 = t_1 - \frac{945}{2Wc_p}$$

and from equation (2)

$$Q_{2-3} = 945 = h_{2-3}\left(t_1 - \frac{945}{2Wc_p} - 75\right) \qquad (9)$$

which can be rewritten as

$$h_{2-3} = \frac{945}{t_1 - 75 - \dfrac{945}{2Wc_p}} \qquad (9a)$$

The selection of the duct air temperature which may be used in the heated wing is influenced by such practical considerations as the quantity of air passed, the availability of heat, and the critical temperature of the structural material employed in the wing. A study of the influence of these factors leads to the conclusion that if aluminum alloys are used in the wing construction, the highest duct temperature allowable on a basis of the material critical temperature should be employed. Inasmuch as most aluminum alloys lose strength rapidly at temperatures above 200° F., a maximum of 300° F duct air temperature has been set for laboratory investigations which involve these materials. It is believed that if carefully designed, 300° F duct air temperature may be used without detrimental effect to the strength of the wing or other protected members. When ferrous alloys are employed other factors determine the maximum allowable duct air temperature, principal among which is the exhaust-air heat exchanger efficiency. With increased duct air temperature, the specific heat of air is increased, the duct size is decreased and the drag effect involved as a result of removing momentum from the ducted air is decreased, all of which are favorable trends.

The quantity of air W and duct air temperature t_1 determine the total quantity of heat directed to the wing surface. The total quantity of heat for a wing surface which will give satisfactory protection has been given in reference 1 as about 1000 Btu/sq ft, hr. The data recorded from the tests of reference 1 were obtained with an exhaust tube in the leading edge of the wing and with an air-heating system in the leading edge of the stabilizer. The data taken with the air-heating system indicated that satisfactory ice protection might be possible with less than 1000 Btu/ft^2 hr average heating delivered to the wing surface. Preliminary considerations of the air-heated-wing anti-icing system for the Lockheed 12A airplane will be based on an average heating requirement of about 800 Btu/sq ft, hr for the entire wetted surface.

Inasmuch as the protected area of the Lockheed 12A airplane is about 200 square feet of wetted surface, the total heat to be directed to the wing will be about 160,000 Btu/hr. When the air temperature in the inlet duct, region 1, is chosen, the weight of air will be established. The delivered heat is measured on a basis of the rise above ambient air temperature. The total delivered heat will not be fully applied, some being lost with the air at the trailing-edge discharge louvers. Taking the loss at the discharge louver into consideration, it may be seen that the unit area heating actually applied to the wing skin is less than 800 Btu/sq ft, hr.

The pressure drop along the gap is given in equation (6). Over the range of Reynolds number values of interest in the present problem the friction coefficient is given by

$$f = \frac{16}{Re} \tag{10}$$

but as noted above $Re = \frac{W}{\mu}$ therefore

$$f = 16\,\mu/W \tag{10a}$$

The term $\dfrac{G^2(v_5 - v_1)}{g}$ is negative and small and will be omitted as a means of simplifying the pressure relations in the heating system. The rate of pressure drop in the gap along the streamlines is given then by

$$\frac{\Delta p}{\Delta N} = \frac{fG^2 v_{av}}{2\ gm} \tag{11}$$

or

$$\frac{\Delta p}{\Delta N} = \frac{16 \mu W v_{av}}{d^3\ g} \tag{11a}$$

and

$$\frac{\Delta p}{\Delta N} = 0.2155 \times 10^{-8}\ \frac{Wv}{d^3} \tag{11b}$$

in which values for μ and g have been substituted.

$$\mu = 5.62 \times 10^{-2}\ \text{lb/ft hr}$$

$$g = 4.18 \times 10^{8}\ \ \text{ft/hr}^2$$

The available pressure drop along the air path from the exhaust-air heater inlet to the discharge louvers is assumed to be 80 percent of the dynamic pressure. It is believed that the lowest airspeed at which prolonged ice protection will be required is at the speed of maximum range. The indicated airspeed of maximum range for the NACA ice research airplane is about 135 miles per hour and this value is employed in these calculations. If 50 percent of the available pressure drop is employed by the heater, there remains 50 percent of 80 percent, or 40 percent, available for the wing circulation. Unreported NACA flight test experience supports these assumptions. Forty percent of the dynamic pressure at 135 miles per hour, indicated airspeed, is 18.65 pounds per square foot. The gap length along the streamlines at the root or longest chord section is 1.25 feet in the Lockheed 12A airplane. The available pressure drop per foot is

$$\Delta p = \frac{18.65}{1.25} = 14.9 \text{ lb/sq ft}$$

Equations (7b), (9a), and (11b) are employed in selecting the size of gap which forms region 2 in figure 1. The temperature of air in the duct, region 1, has been taken as 200°, 300°, 400°, and 500° F in the analytical study.

RESULTS OF CALCULATIONS

The relations between W and h as expressed in equations (7b) and (9a) for t_1 = 200°, 300°, 400°, and 500° F and d = 0.005, 0.0078, 0.01, 0.015, and 0.02 have been calculated and are given in figure 2. Preliminary studies of the problem indicated the desirability of the ranges employed. The relations between $\Delta p/\Delta N$ and W, as expressed in equation (11b) for the same range of values of d, have been calculated and are given in figure 3. The design analyses for the graphical relations shown in figures 2 and 3 are valid at all span stations if the necessary quantity of heated air reaches each station. The duct section area in the Lockheed 12A airplane design has been selected so that the pressure drop across region 2 at the wing root is equal to the drop along the duct, region 1, added to the drop across region 2 at the wing tip. Such a design should give a nearly uniform spanwise skin temperature rise above ambient air.

MODEL TESTS

Before making alterations to the Lockheed 12A airplane for the provision of heated-air ice prevention on the wings, a model leading edge was constructed and tested to determine the validity of the results shown in figures 2 and 3. The test airplane wing is constructed of aluminum alloy and the leading edge is subjected to span loading stresses. The design of the model was therefore based on a maximum duct temperature of 300° F. At this temperature the total weight of air required to deliver 160,000 Btu/hr to the wing will be approximately 2000 lb/hr. The protected span is 14½ feet so that, assuming uniform distribution, the weight of air through each gap is about 70 lb/hr, ft. Referring to figure 2, the optimum gap for these conditions is found to be 0.02 foot or approximately 1/4 inch. A gap of 3/32 inch was used in the model leading edge because of the lower heat quantity available for the tests.

The model (fig. 4) consisted of a 3-foot leading-edge span with five ribs spaced at 9 inches on centers. The inner and outer skins were separated by a 3/32-inch-thick spacer at each rib. The chord length of the model corresponds to $13\frac{1}{2}$ percent of a 7-foot-chord wing. Although the Lockheed 12A airplane wing employs an NACA 2412 airfoil, an NACA 0012 section was chosen to simplify the tests. Figure 5a shows a typical section through the rib illustrating the construction details.

The design of the model was such as to permit a static structural test as well as a study of the thermal pressure relations. The thermal tests were conducted by forcing air from a centrifugal blower through an electric heater and the model leading edge. The quantity of air was measured by the use of a sharp-edge orifice meter. The temperatures of the model skin and of the air passed through the duct and leading-edge gap were measured by iron-constantan thermocouples. The thermocouple locations at one chord station are shown in figure 5a. The pressures of the air passed through the model were measured by the use of static pressure orifices located at the points shown in figure 5a. The thermocouples and pressure orifices shown in the transverse section (fig. 5a) were installed at 3 span stations in the model.

The exterior surface of the model was cooled by a water spray, which, while not precisely simulating the removal of heat by the air stream, was satisfactory for the purpose of the tests.

The tests were conducted by passing air at several temperatures and weight rates through the model and making observations of resultant temperatures and pressures. The temperatures employed in the model tests were lower than would be used to obtain satisfactory icing protection.

At the conclusion of the thermal studies, the design air loads for the Lockheed 12A airplane wing were applied in a static test. The manner in which the loads were applied is given in figure 6.

The results of the model tests have been used to determine the friction coefficient and Nusselts number, $\frac{hd}{k}$, at the test Reynolds number. The relation between Nusselt's number and Reynolds number is given graphically in figure 7. It should be noted that the experimental data of these tests are for heat transferred to one surface only.

The relation between friction coefficient, calculated from the model tests, and Reynolds number is shown on figure 8 with the friction coefficient curve used in equation (10).

As shown in figure 6, the model was found to have satisfactory strength with a load equivalent to the high angle-of-attack condition with a load factor of 6. The total load was 807 pounds, which corresponds to a distributed load of 212 pounds per square foot.

DISCUSSION

The results of the model tests indicate that the preliminary design of the air-heated wing for the Lockheed 12A airplane was satisfactorily developed. The wing, therefore, has been constructed and is currently being tested in flight to determine the thermal properties.

In the preliminary design herein developed, it is planned that the heat absorbed by the boundary-layer air over the leading edge will contribute to the prevention of ice at rearward chord points. The leading-edge heat exchanger presented in this design is a compromise device resulting from practical considerations of airplane construction. While a more efficient heating system would be obtained by extending the double skin over the entire chord, such a design is not considered practical.

While aerodynamic heating may be an important factor in the prevention of ice on high-performance aircraft, it is believed that the design of the heating equipment should be based on the heat available and required at the speed of maximum range. At this speed aerodynamic heating will be unimportant. The effects, therefore, of adiabatic and viscous heating are not considered in this design study.

The point at which the air is discharged from the interior of the airfoil will influence the design. If exhausted at a low-pressure point, the available pressure drop across the heating system may be greater than 80 percent of the dynamic head. It is not at present known whether the discharge of air from a slot near the gap exit, as compared to a discharge near the trailing edge, is superior from the standpoint of ice prevention.

The advantages of the design developed herein may be listed as follows:

1. Preliminary weight studies indicate that the air-heating equipment will weigh less than any other known effective ice-prevention equipment.

2. The maintenance and inspection requirements should be less than other ice-prevention equipment.

3. The performance of the airplane may be improved due to a wing drag reduction which should result from making the wing surface aerodynamically smooth.

4. The heating system may be employed on the ground to remove snow or frost without danger to the wing structure.

5. The use of air heating may permit the air heater to be employed for a combination of functions in addition to wing de-icing, such as cabin air heating, windshield de-icing, gun heating, and winterizing parts which are vulnerable to low ambient air temperatures, and thus effect a further weight reduction.

6. The heated-air system should be less vulnerable to gunfire or other military action such as barrage balloon cables than other de-icing devices.

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REFERENCES

1. Rodert, Lewis A., Clousing, Lawrence A., and McAvoy, William H.: Recent Flight Research on Ice Prevention. NACA A.R.R., Jan. 1942.

2. McAdams, William H.: Heat Transmission. McGraw-Hill Book Co., Inc., 1933.

3. Theodorsen, Theodore, and Clay, William C.: Ice Prevention on Aircraft by Means of Engine Exhaust Heat and a Technical Study of Heat Transmission from a Clark Y Airfoil. Rep. No. 403, NACA, 1931.

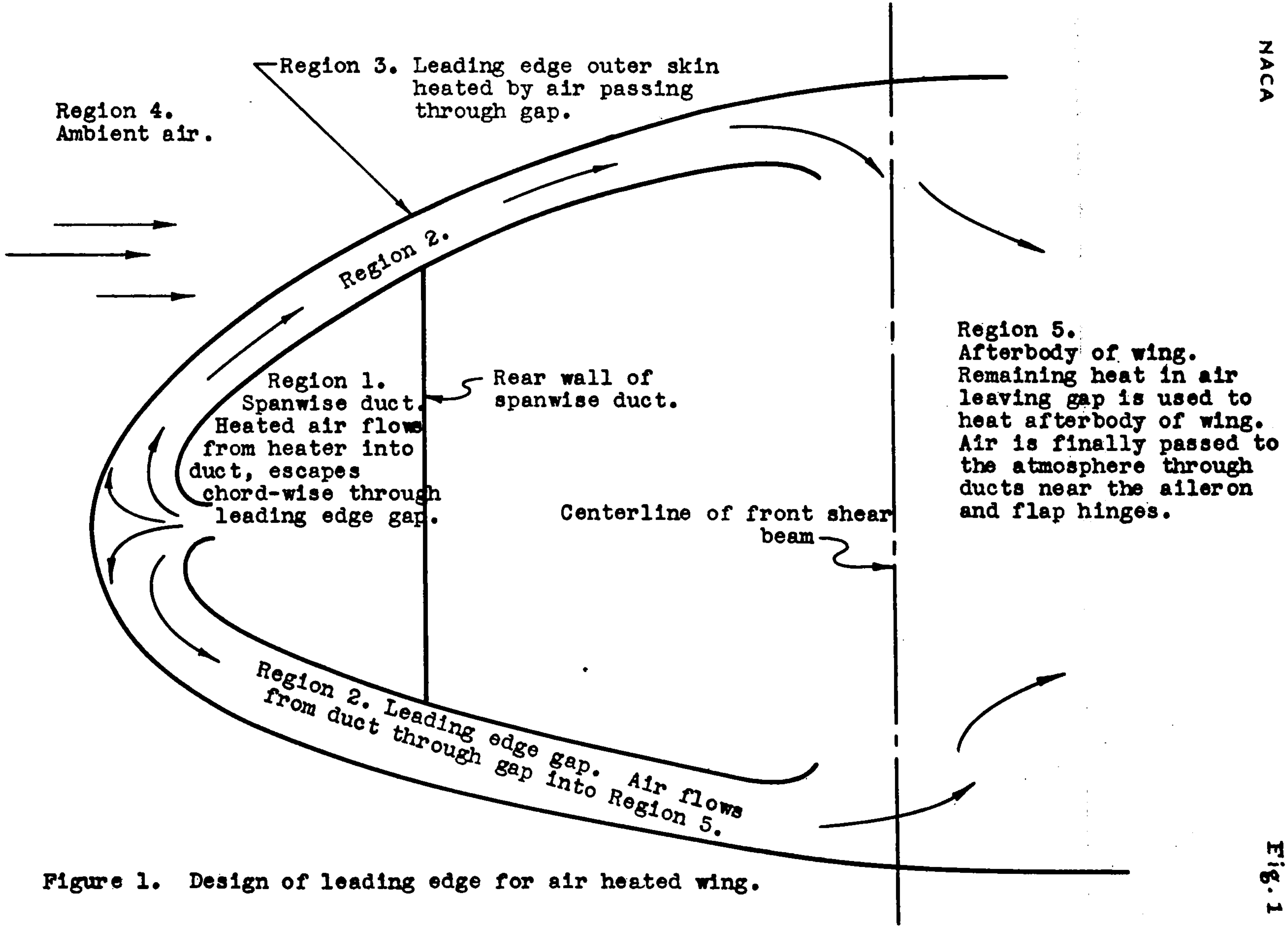

Figure 1. Design of leading edge for air heated wing.

LEGEND

—— $h = 0.0034 \frac{W^{0.8}}{d}$

---- $h = \frac{945}{\left(t_1 - 75 - \frac{945}{2Wc_p}\right)}$

• h Calculated from model leading-edge test data

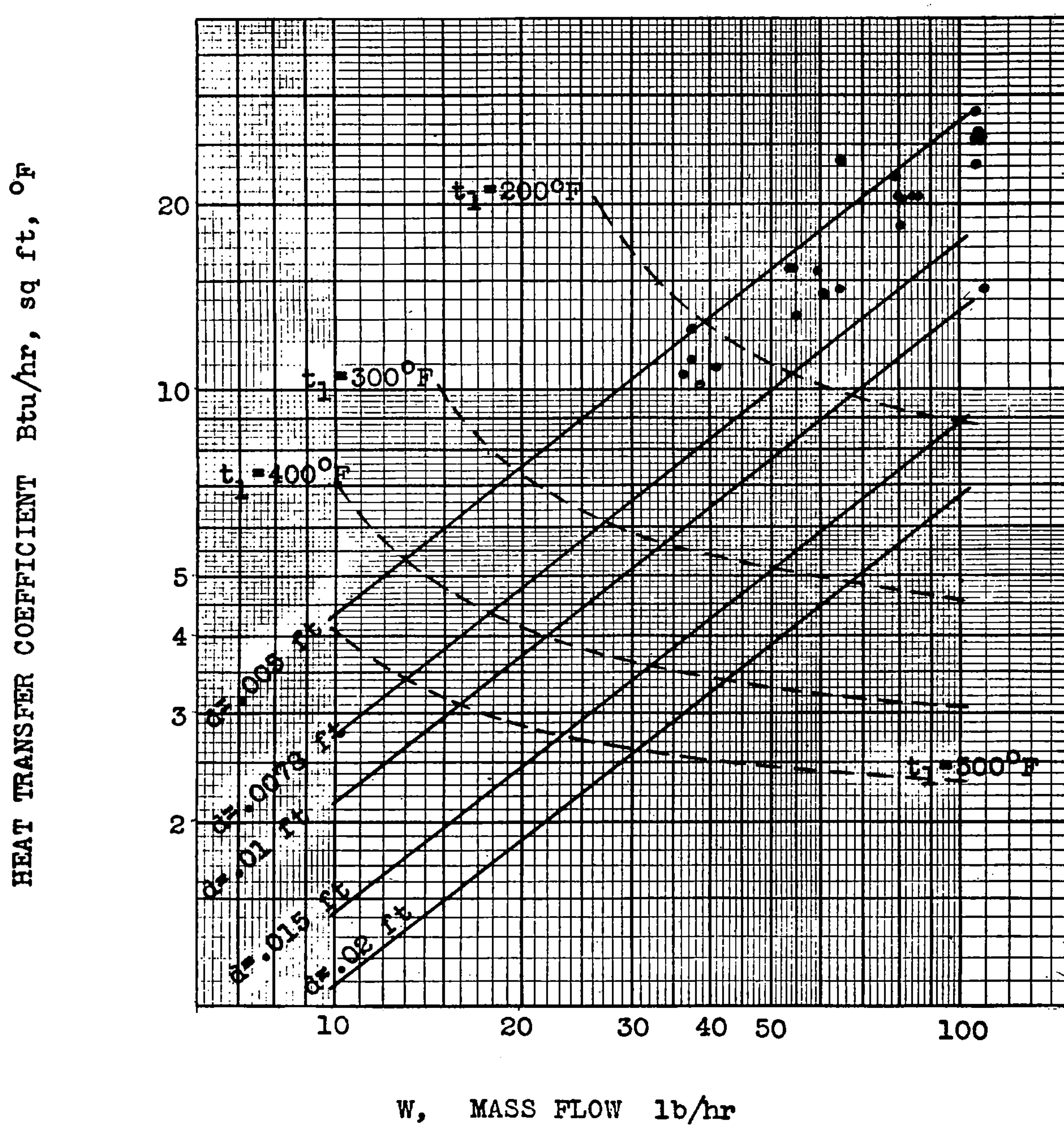

Figure 2.- The relations between heat transfer coefficient, h, and mass flow per foot span, W, for several gap sizes and duct temperatures.

LEGEND

—— $\Delta p/\Delta N = 0.2155 \times 10^{-8}\ Wv/d^3$

● $\Delta p/\Delta N$ Calculated from model leading-edge test data

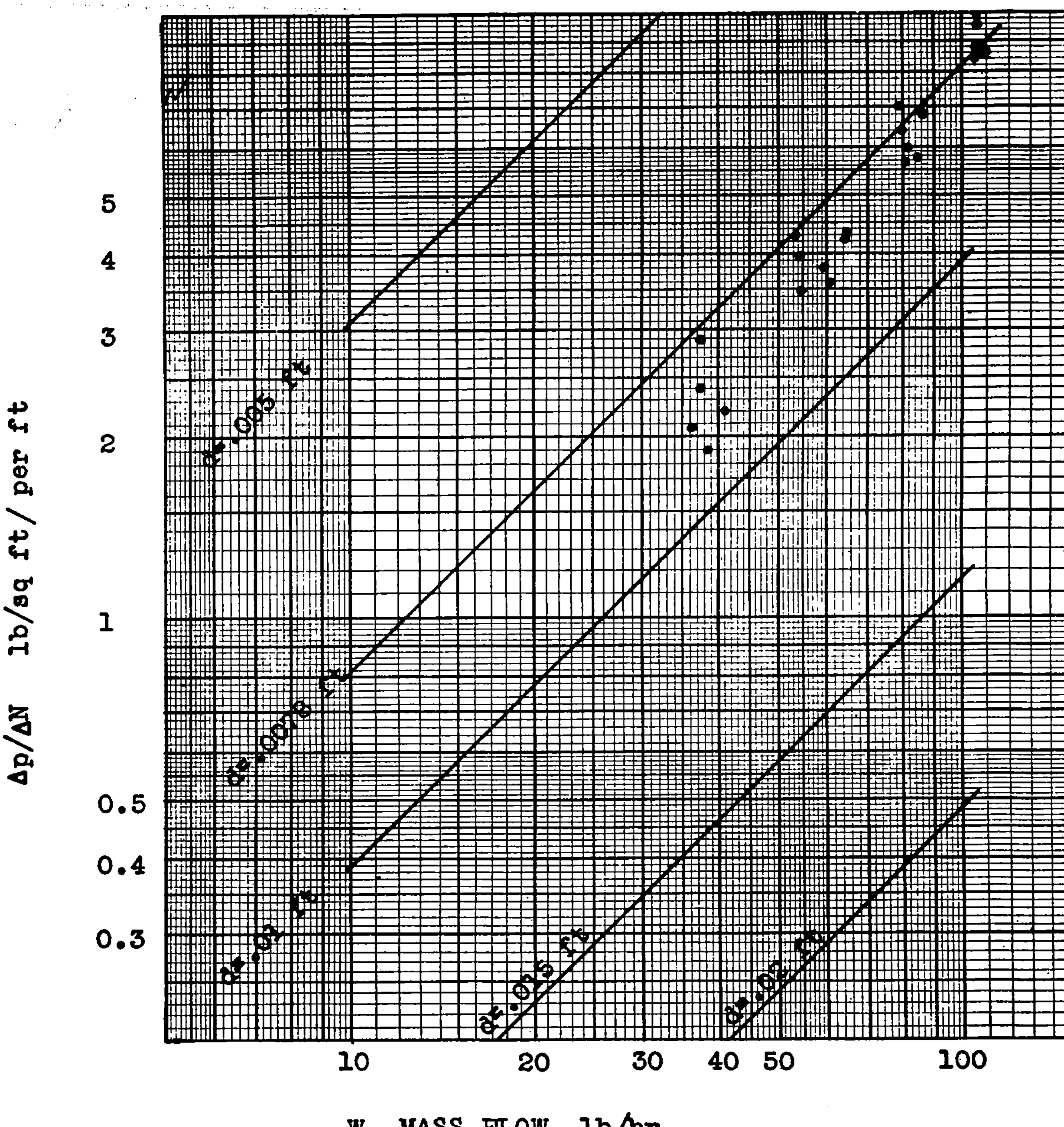

Figure 3.- The relation between the pressure loss gradient, $\Delta p/\Delta N$, and the mass flow per foot span, W, through gap of several thicknesses.

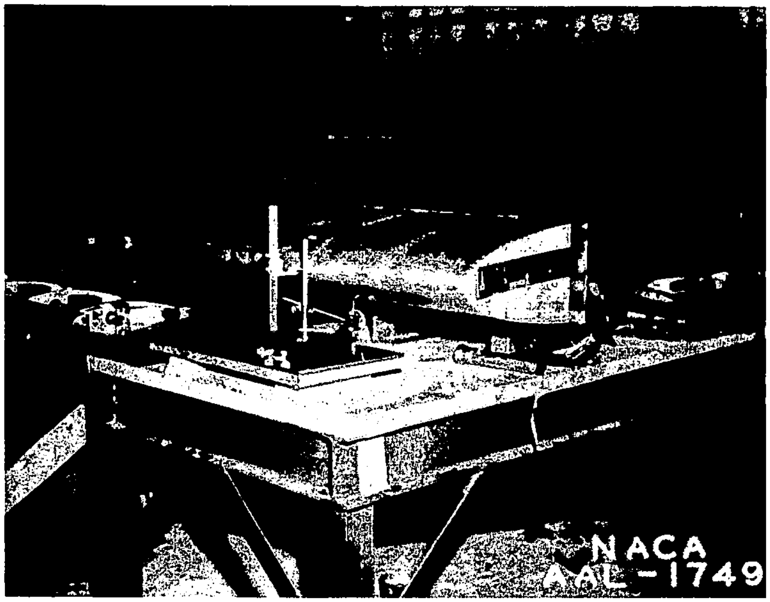

Figure 4.- The model leading edge with which the preliminary design calculations were studied.

Figure 6.- The model heated leading edge being statically loaded. High angle of attack, load factor 6. Applied load 212 pounds per square foot.

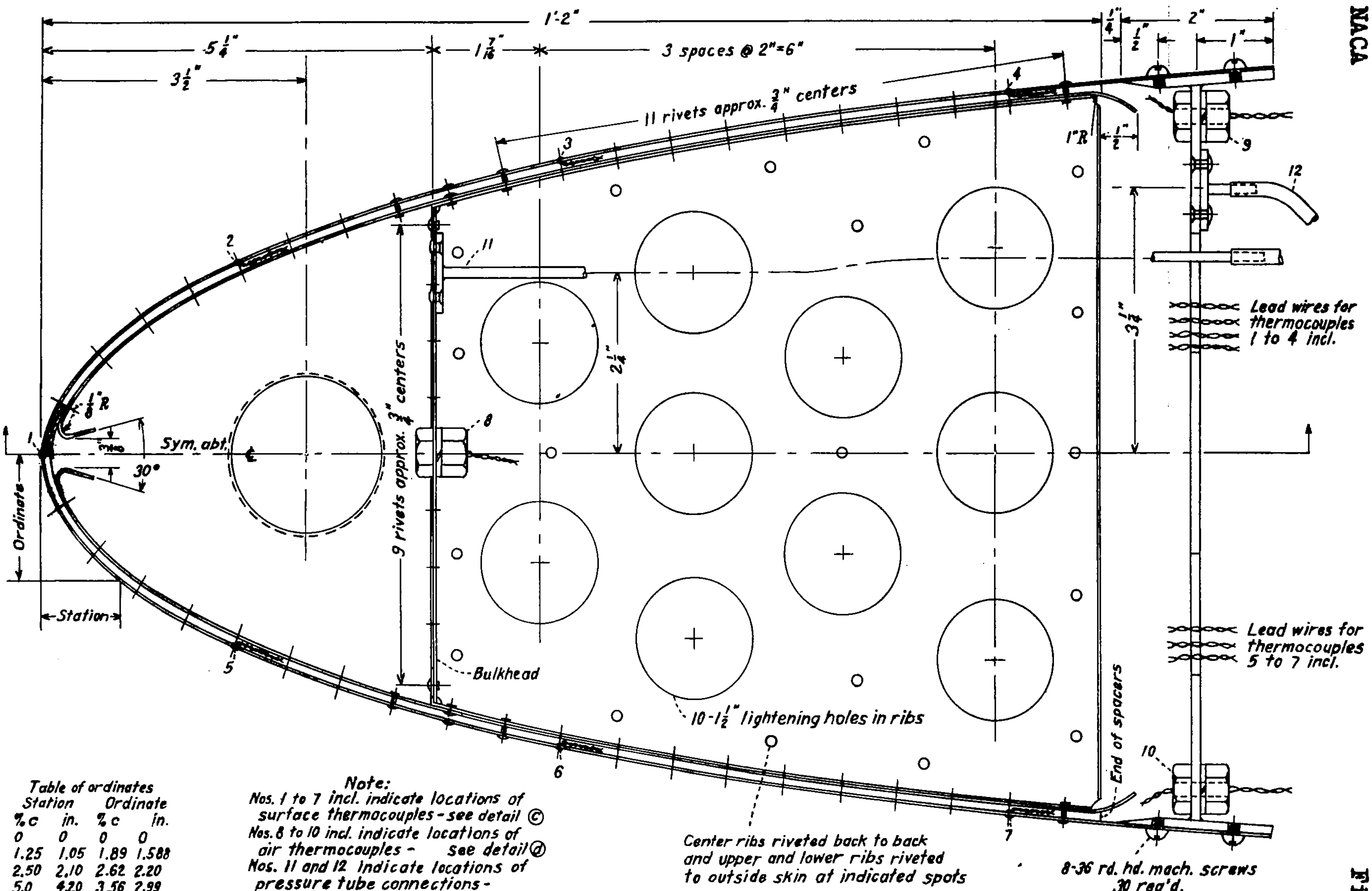

Table of ordinates

Station %c	Station in.	Ordinate %c	Ordinate in.
0	0	0	0
1.25	1.05	1.89	1.588
2.50	2.10	2.62	2.20
5.0	4.20	3.56	2.99
7.5	6.30	4.20	3.528
10	8.40	4.68	3.93
15	12.60	5.34	4.48
20	16.80	5.74	4.82

Figure 5a.- Transverse section through model heated leading edge showing thermocouple and static pressure orifice locations.

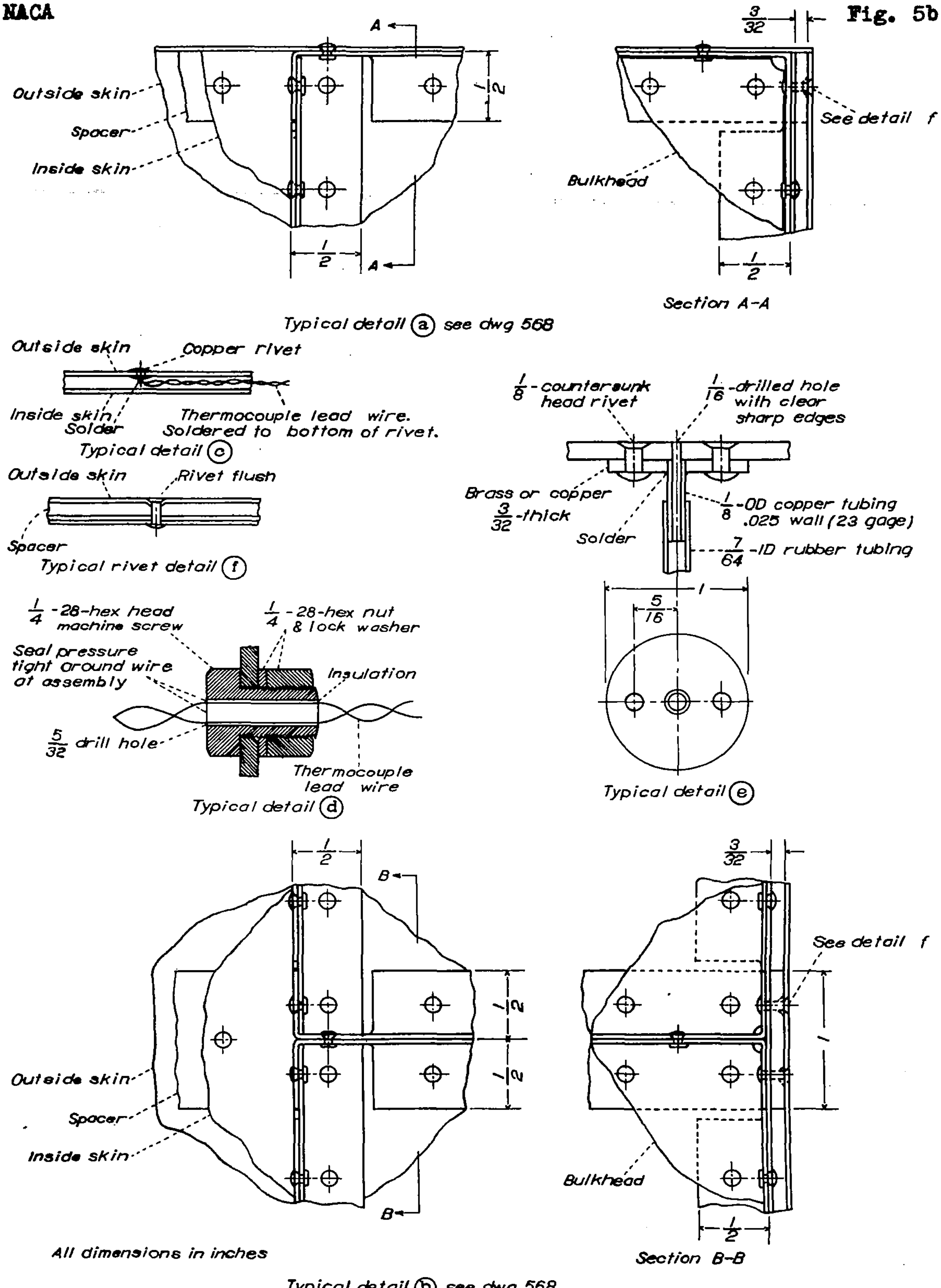

Figure 5b.- Details of construction of the model heated-leading edge of wing. In connection with figure 5a.

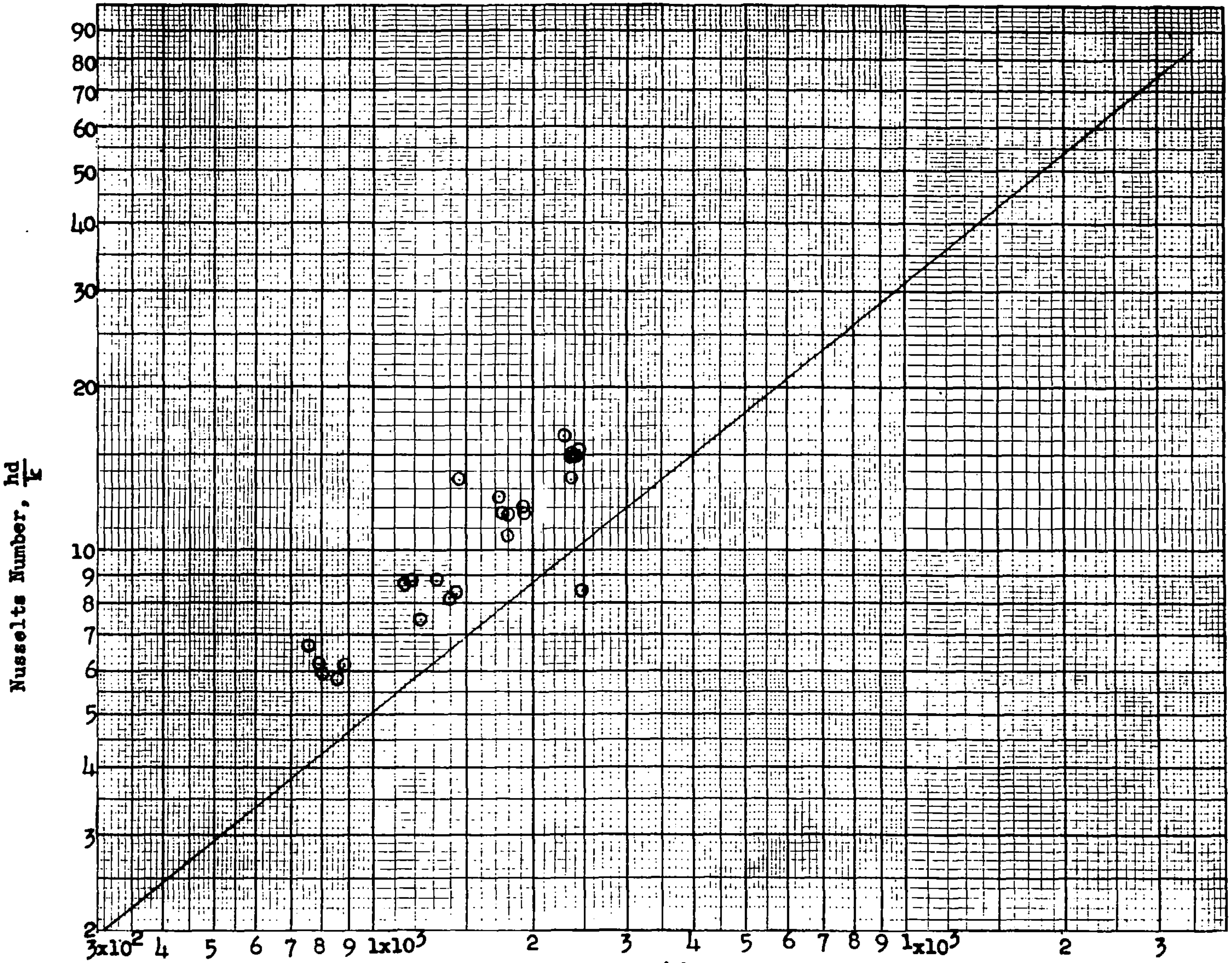

Figure 7. The relation between Nusselts Number, $\frac{hd}{k}$, and Reynolds Number, $\frac{dG}{\mu}$, from model test data and the equation $\frac{hd}{k} = 0.0225 \left(\frac{dG}{\mu}\right)^{0.8} \left(\frac{c_p\mu}{k}\right)^{0.4}$

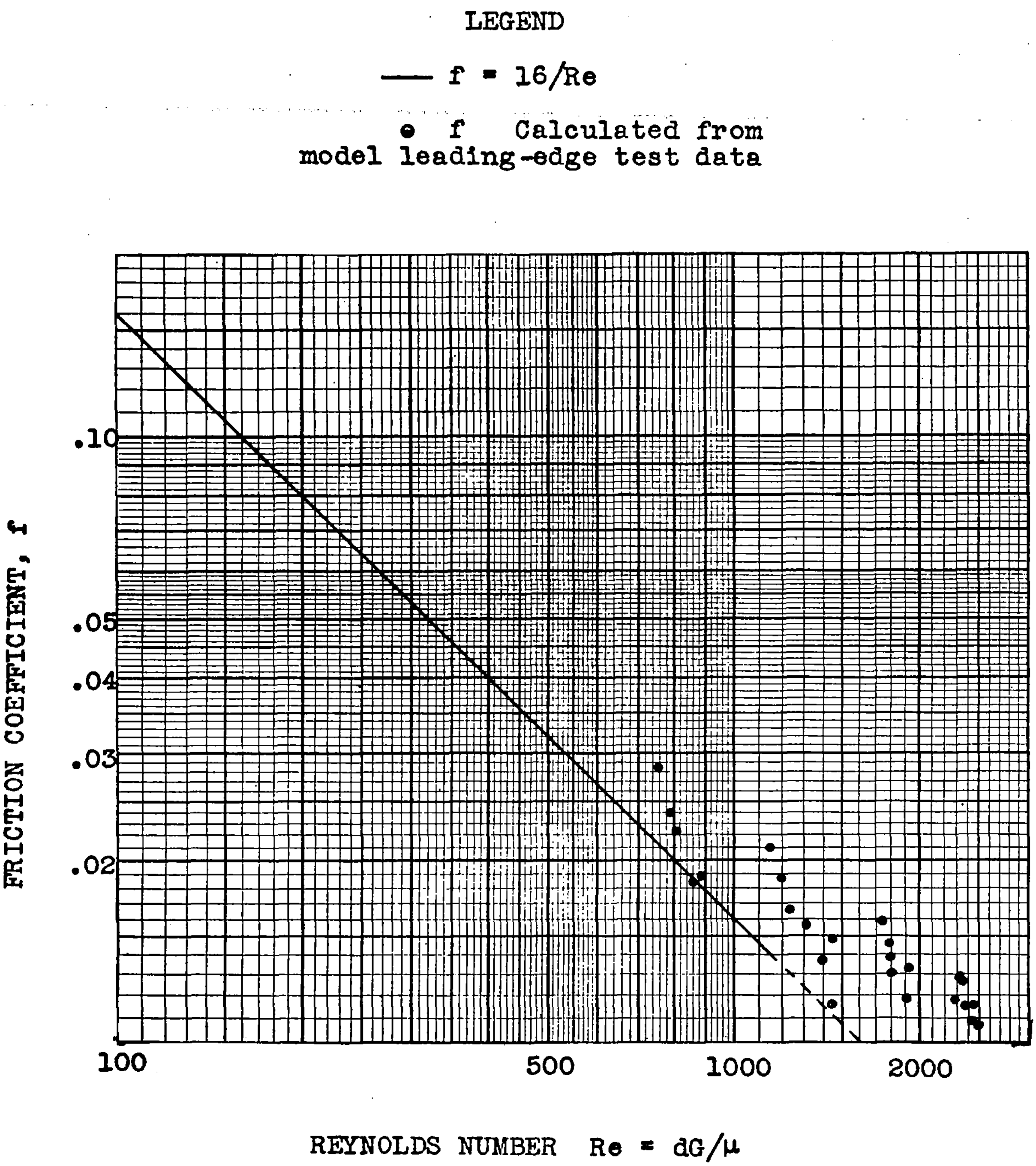

Figure 8.- The relation between friction coefficient, f, and Reynolds number, Re, assumed for preliminary design.